NON-THERMAL BEHAVIOR IN MULTIFRAGMENT DECAY

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Highly excited nuclear systems have been observed to decay into several intermediate mass fragments (IMFs :$3 \leq Z \leq 20$).[1,2] Multifragment decay signals the response of nuclear matter to extreme conditions of temperature and pressure and thus might provide insight into the nuclear equation-of-state away from equilibrium. Recent evidence suggests that the multifragment decay indicates emission from a low density nuclear system.[1,2] Other defining characteristics of the fragmenting system such as its excitation, however, remain poorly understood.

To explore the systematics of multifragmentation, we have studied several systems over a large range of bombarding energies at the National Superconducting Cyclotron Laboratory. These systems include ^{14}N+^{197}Au at E/A = 100-156 MeV, ^{36}Ar+^{197}Au at E/A = 35-110 MeV, ^{84}Kr+^{197}Au at E/A = 35-70 MeV, and ^{129}Xe+^{197}Au at E/A = 40-60 MeV. The ^{84}Kr+^{197}Au experiment is representative of the type of data taken for these reactions. Light charged particles and IMFs produced in the collisions were detected in the angular range $5.4° \leq \theta_{lab} \leq 160°$ by the MSU Miniball/Washington University Miniwall 4π detector array. The energy resolution for this experiment was 15%. A more detailed description of the experiment has been previously reported.[3]

In this analysis, we focus on the extent to which the excitation energy is equilibrated in these reactions. In order to select collisions resulting in a composite system with the highest excitation and the least angular momentum, we have constructed an impact parameter scale using the charged-particle multiplicity[4] and selected high multiplicity events. For all reactions, events were selected with $b/b_{max} \leq 0.2$.

The kinetic energy spectra for boron fragments emitted in central collisions of ^{84}Kr projectiles with ^{197}Au target nuclei at E/A = 55 MeV are shown in Fig. 1a. These kinetic energy spectra are Boltzmann-like distributions that exhibit an angular dependence. The more forward angles have a less steep exponential tail showing a non-negligible probability for preferential emission of high energy fragments at forward angles even for central collisions. To eliminate the trivial momentum of the composite system along the beam axis due to the momentum transfer from the projectile, we have examined the transverse kinetic energy, defined as $E_{trans} = E \sin^2 \theta$, where E and θ are the laboratory energy and emission

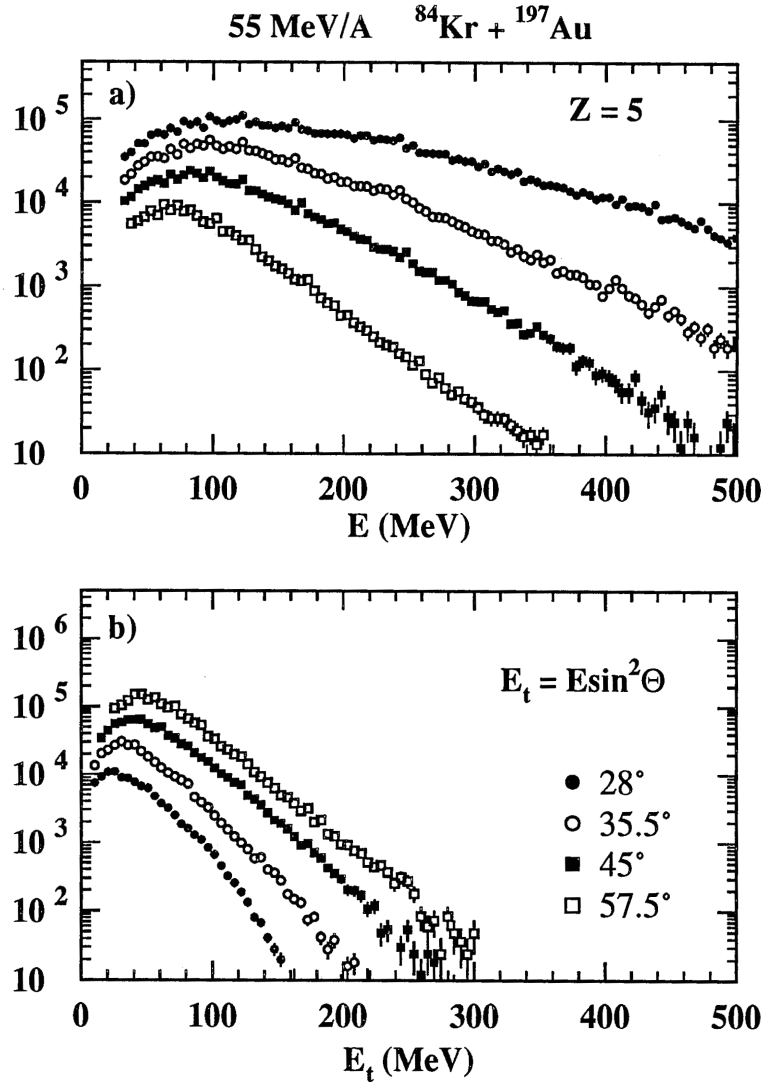

Figure 1. a) Kinetic energy spectra of boron fragments emitted in central collisions of the reaction ^{84}Kr+^{197}Au at $E/A = 55$ MeV. b) Transverse kinetic energy spectra constructed from the spectra shown in a).

angle, respectively. In the absence of collective effects, the transverse kinetic energy should represent a good measure of the thermalized energy available to the fragments. The transverse kinetic energy distributions constructed from these spectra are displayed in Fig. 1b. The high energy portion of these spectra can be characterized by a simple exponential. As can be seen in Fig. 1b, the slope of this exponential changes very little as a function of angle. Note that the distribution at 57.5° dominates the tail of the distribution. General sequential statistical decay models predict that the high energy portion of the spectrum is populated by emission from systems of the highest excitation while the low energy portion of the spectrum is populated by emission during later stages of the de-excitation cascade from a less excited system. The asymptotic logarithmic slopes of the transverse kinetic energy distributions therefore may provide information about the initial excitation of the composite system.

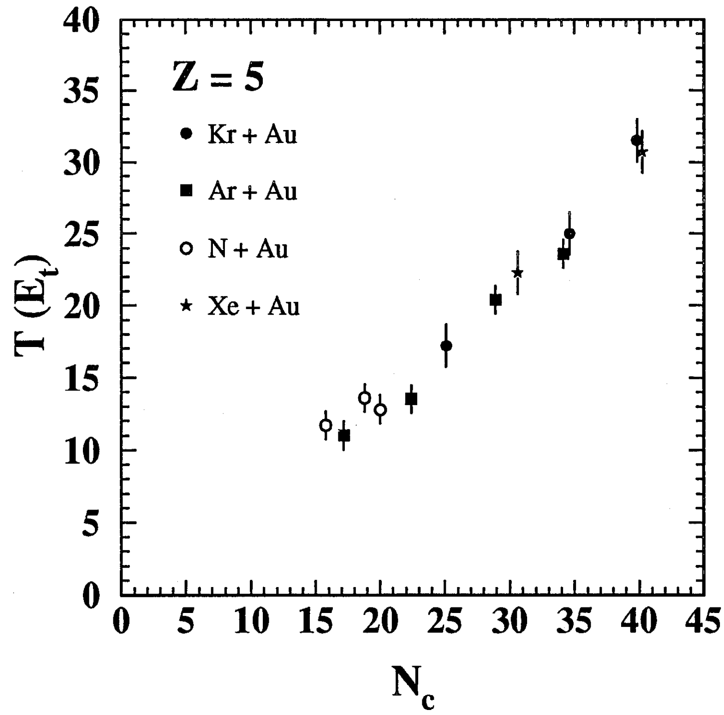

Figure 2. Extracted slopes from the transverse kinetic energy distributions for boron fragments emitted in central collisions. The beam energies represented for each system are described in the text.

In Fig. 2, the slope parameters for boron fragments produced in the different reactions are plotted versus the multiplicity associated with central collisions. The open circles represent the ^{14}N+^{197}Au system at E/A = 100, 130, and 156 MeV; solid squares depict ^{36}Ar+^{197}Au at E/A = 35, 50, 80, and 110 MeV; solid circles represent ^{84}Kr+^{197}Au at E/A = 35, 55, and 70 MeV/A ; the solid stars indicate the ^{129}Xe+^{197}Au system at E/A = 40 and 60 MeV. A linear trend is evident for all these systems, which span N_C from 15 to 38 and T (slope parameter) from 11 to 31.5 MeV. For the lightest projectiles studied, ^{14}N, the slope of $T(E_t)$ with respect to N_C is nearly flat, indicating a saturation of energy deposition for light heavy-ions (A$\leq$20) by a nucleon-nucleon collision mechanism in this energy range. The magnitude of the measured slope parameter is also interesting. For the heaviest beams at the highest incident energies, the slope parameter reaches values greater than 30 MeV. Such large values of the slope parameter, far in excess of the binding energy of the system are too high to be attributed to a thermal temperature of the system.

If the multiplicity is proportional to the excitation energy of the system, and the slope parameter is proportional to the temperature of the system, then an increasing monotonic relationship between these two quantities is expected. A similar relationship between multiplicity and the deduced excitation of the system has recently been observed within a single system.[5] If a Fermi gas model were appropriate and the level density assumed to be constant, a quadratic relationship between these two variables would be expected. The reason for the lack of a quadratic relationship between the multiplicity and slope parameter might be the dependence of the level density on excitation energy and source volume. Distortions of this trend imposed by residual angular momentum effects have yet to be investigated. Essentially, the same trend is observed for all IMFs in the range 3$\leq$ Z $\leq$9, as indicated by the error bars shown in Fig. 2.

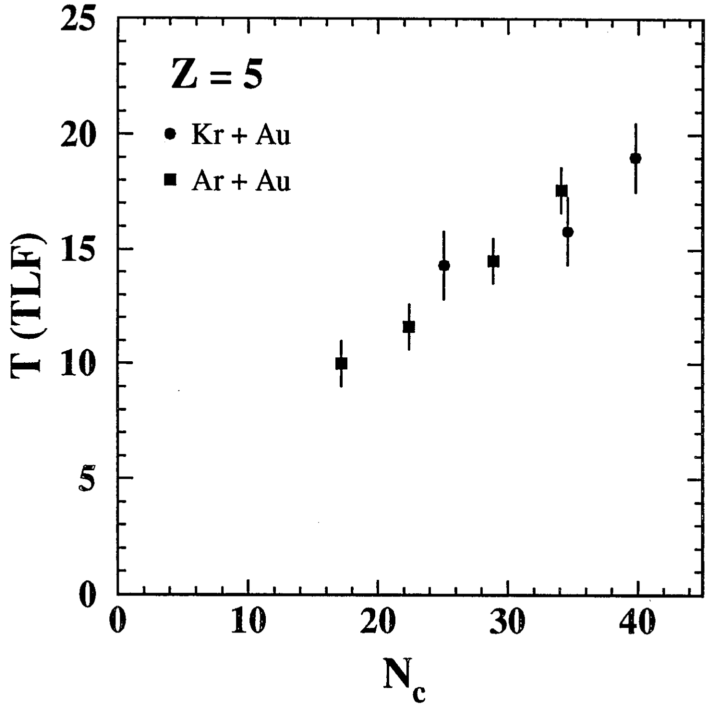

Figure 3. Slope parameters of the target-like source from moving-source fits of boron kinetic energy spectra. The beam energies represented for each system are described in the text.

An additional consideration in the interpretation of the trend observed in Fig. 2 is the emission of IMFs from multiple sources. The multiple source nature of the IMF emission is evident from the failure to fit the energy spectra and angular distributions with a single isotropically-emitting moving source. The emission at backward angles ($\theta_{lab} \geq 90°$) can be characterized by a target-like residue while emission at forward and middle angles ($\theta_{lab} \leq 90°$) manifests a component attributable to emission from a source of intermediate rapidity. The importance of the intermediate rapidity source increases with increasing projectile mass. We have performed moving-source fits of the kinetic energy spectra and angular distributions from the ^{36}Ar+^{197}Au and ^{84}Kr+^{197}Au systems to assess the contributions of the two sources. The target-like source is characterized using only detectors at backward angles where the cross-section is dominated by equilibrium emission. The second (non-equilibrium) source moves with a higher source velocity and has a more forward-peaked angular distribution in the laboratory. The slope parameters for the target-like source of boron fragments from the ^{36}Ar+^{197}Au and ^{84}Kr+^{197}Au systems are plotted versus multiplicity in Fig. 3. The slope parameter does not exceed 20 MeV for this source, suggesting that the slope parameter of the transverse kinetic energy distribution can be attributed to the non-equilibrium source. More detailed simulations consisting of two isotropically-emitting sources have shown that the slope parameter of the transverse kinetic energy distribution is approximately equal to the apparent temperature of the non-equilibrium source. The physical origin of this large apparent temperature for IMF emission associated with central collisions is presently unclear; however, it is certainly too large ($T = 30$ MeV) to represent a thermal temperature.

In summary, we have observed a linear trend between the slope parameter of the transverse kinetic energy distribution for IMFs and the charged-particle multiplicity associated with central collisions. The largest values observed for the slope parameter (more than 30

MeV) are attributable to the non-equilibrium source and are not understandable in terms of a purely thermal source. The large magnitude of the slope parameter for the heaviest projectiles at the highest incident energies studied could be due to the onset of collective effects. Experimental evidence for a collective expansion has been reported for several heavy-ion systems at intermediate energies.[6–8] Comparisons are planned with a quantum molecular dynamics (QMD) model[9] and a Boltzmann-Uehling-Uhlenbeck (BUU) model[10] to investigate the predictions for collective behavior.

We would like to acknowledge Dr. L. Phair and our colleagues at Lawrence Berkeley Laboratory for helpful discussions and for providing us with the $^{129}Xe+^{197}Au$ data.

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